

**Claims**

1. A mixed-mode fuel injector comprising:
  - (i) a nozzle body (5) comprising passages for fuel, an inner cylindrical space for receiving a needle valve, and a conical surface (C) close to the tip (7) of the nozzle body for guiding a spray of fuel;
  - (ii) a needle valve (1), which has a converging-diverging conical head for guiding a spray of fuel and which is movable back and forth and received in said nozzle body, wherein said needle valve is at a biased closing position or an opening position defined by driving means; and
  - (iii) a micro-variable-circular-orifice (4) comprising a variable circular ring aperture between said needle valve and said nozzle body,  
such that fuel is dischargeable in variable sprays of conical and conical-multi-jet shapes through said micro-variable-circular-orifice by lifting said needle valve at different magnitudes.
2. A mixed-mode fuel injector according to claim 1, wherein the micro-variable-circular-orifice (4) further comprises a plurality of micro-channels (6).
3. A mixed-mode fuel injector according to claim 1 or 2, wherein the conical surface (C) has a single conical surface.
4. A mixed-mode fuel injector according to claim 1 or 2, wherein the conical surface (C) is an integrated conical surface having two or more conical surfaces with different conical angles connected together.
5. A mixed-mode fuel injector according to claim 1 or 2, wherein the conical surface (C) is a diverging curved surface.
6. A mixed-mode fuel injector according to claim 1 or 2, wherein the needle lift for the opening position is approximately in the range of 0-300 $\mu$ m, the needle head diameter is approximately in the range of 0.8-3.5mm, and the angle between the centerline of the nozzle body (5) and the inner conical surface (C) at the nozzle body tip (7) is approximately in the range of 35-75 degrees.
7. A mixed-mode fuel injector according to claim 2, wherein the plurality of micro-channels (6) is on the said conical surface (C) with cross sections that are one or more of semi-circles, arcs, triangles, trapezoids or other polygons.

8. A mixed-mode fuel injector according to claim 2, wherein the needle head (3) remains at least partially received within the tip (7) as the needle valve (1) is moved back and forth between the biased closing position and opening position such that when fuel is injected through the micro variable aperture (4) between the needle head and said conical surface of the nozzle body, fuel is also injected through the multiple micro-channels (2), the upper surface of the needle head and the conical surface serve as guiding surfaces for fuel sprays.
9. A mixed-mode fuel injector according to claim 7, wherein there are about 4-20 micro-channels (6) with the cross-section of semi-circles with the diameters approximately in the range of 50-300 $\mu$ m.
10. A mixed-mode fuel injector according to claim 7, wherein there are about 4-20 micro-channels (6) having a cross-section other than semi-circles with the maximum dimension approximately between 50-400 $\mu$ m.
11. A mixed-mode fuel injector according to any of claims 2 to 10, wherein the sizes of said micro-channels (6) are the same.
12. A mixed-mode fuel injector according to any of claims 2 to 10, wherein the sizes of the micro-channels (6) are different depending on specific needs of atomization.
13. A mixed-mode fuel injector according to any of claims 2 to 12, wherein the said micro-channels (6) are distributed on or under the conical surface (C) so that they are open channels or closed channels.
14. A mixed-mode fuel injector according to claim 2, has a plurality of micro-channels underneath the said conical surface (C), forming a sac-hole or valve-covered-orifice multi-hole type injector through blocking the circular aperture by the needle head at a predefined needle-lift range.
15. A mixed-mode fuel injector according to claim 2, wherein different shapes of fuel sprays are generated by changing the magnitude of lift of said needle valve (1) and the needle valve is arranged within the nozzle body (5) so that, at low to medium injection loads, fuel is mainly injected through the variable circular aperture between the needle head (3) and nozzle body (1), thus mainly forms a conical shape spray, while at high injection loads, fuel is injected through both the variable circular aperture between the

needle head and nozzle body and the micro-channels (6), thus forms a mixed-mode conical-multi-jet shape spray, whereby provides different atomization desired by engine combustion at different loads.

16. A mixed-mode fuel injector according to claim 2, wherein different shapes of fuel sprays are generated by changing the magnitude of lift of said needle valve (1) and the needle valve is arranged within the nozzle body (5) so that, at low to medium injection loads, fuel is mainly injected through the variable circular aperture between the needle head (3) and nozzle body, thus mainly forms a conical shape spray, while at high injection loads, the needle head can completely or partially block the variable circular aperture, whereby fuel is fully or mainly injected through the micro-channels (6), which can be open channels or closed channels depending on penetration needs, thus mainly forms conventional multi-hole sprays at high loads, whereby provides different penetration desired by engine combustion at different loads.

17. A mixed-mode fuel injector according to claim 1 or 2, wherein the fuel channel between the needle valve (1) and the nozzle body (5) is of converging-diverging shape and by lifting said needle valve at different magnitudes, the minimum cross-section is at the sealing surface during the early stage of fuel injection, the minimum cross-section is at said micro-variable-circular-orifice (4) or at the sealing surface during the middle stage of fuel injection, and the minimum cross-section is at the sealing surface again during the late stage of fuel injection, whereby it has means of ensuring fine atomization during all fuel injection stages.

18. A mixed-mode fuel injector according to claim 1 or 2, wherein the angle between the centerline of the conical surface (C) and the centerline of the nozzle body (5) is approximately 0-15 degrees, depending on an angle between a centerline of the fuel injector and a centerline of a piston in an engine cylinder.

19. A mixed-mode fuel injector according to any of the preceding claims, wherein the fuel injected is one or more of diesel fuels, gasoline fuels, alternative fuels, mixtures of water and fuels, pure water or liquid exhaust cleaning additives in which case, the fuel injector is a general purpose injector.

20. A mixed-mode fuel injector according to claim 1, wherein the needle valve (1) is passively driven by high fuel pressure which provides said driving means.

21. A mixed-mode fuel injector according to claim 1, wherein the needle valve (1) is actively driven by an actuator which provides said driving means.

22. A mixed-mode fuel injector according to claim 21, wherein the actuator is a solenoid or a piezo actuator.

23. A mixed-mode fuel injector, which has a micro-variable-circular-orifice (MVCO) comprising a variable circular ring aperture and multiple-micro-channels as in claim 2, wherein the MVCO is used as a sole orifice or in-combination with other multi-hole conventional orifice.